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Analysis of Single-hole and Cross-hole Tracer Tests Conducted at the Nye County Early Warning Drilling Program Well Complex, Nye County, Nevada

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Abstract –*As part of the effort to understand the flow and transport characteristics downgradient from the proposed high-level radioactive waste geologic repository at Yucca Mountain, Nevada, single- and cross-hole tracer tests were conducted from December 2004 through October 2005 in boreholes at the Nye County 22 well complex. The results were analyzed for transport properties using both numerical and analytical solutions of the governing advection dispersion equation. Preliminary results indicate effective flow porosity values ranging from 1.0×10^{-2} for an individual flow path to 2.0×10^{-1} for composite flow paths, longitudinal dispersivity ranging from 0.3 to 3 m, and a transverse horizontal dispersivity of 0.03 m. Individual flow paths identified from the cross-hole testing indicate some solute diffusion into the stagnant portion of the alluvial aquifer.*

I. INTRODUCTION

In order to understand the fate and transport of any radionuclide plume that might reach the saturated zone from the proposed high-level radioactive waste geologic repository at Yucca Mountain, Nevada, and make its way through to the alluvium downgradient, the transport characteristics of the alluvium, in addition to those of the fractured tuffs beneath the repository, need to be determined. Nye County, Nevada, in cooperation with the U.S. Department of Energy (DOE), is conducting hydraulic and tracer tests at Site 22 of the Nye County Early Warning Drilling Program , NC-EWDP-22 (the Nye 22 Complex), Figure 1, as a continuation of the 2000-2002 effort of characterizing the transport characteristics of the alluvium with hydraulic and tracer tests at the Alluvial Testing Complex, ATC (Figure 1). Since January 2004, the U.S. Geological Survey (USGS) and the Los Alamos National Laboratory (LANL), working under the DOE Yucca Mountain Project, have had a consulting, overseeing, and supporting role in this latest round of testing; they are in the process of conducting independent analyses of the data. The purpose of this paper is to present an analysis by the USGS of some of the tracer tests that have been conducted at the Nye 22 Complex and the resulting preliminary transport parameters. The data were obtained through Nye County's Independent Scientific Investigations Program and DOE's Sample Management Facility. Chemical analyses of water samples to obtain tracer concentrations were conducted by the University of Nevada at Las Vegas / Harry Reid Center for Environmental Studies (UNLV/HRC).

II. WORK DESCRIPTION, RESULTS, AND DISCUSSION

The Nye 22 Complex consists of four wells, NC-EWDP-22S (22S), NC-EWDP-22PA (22PA), NC-EWDP-22PB (22PB), and NC-EWDP-22PC (22PC), laid out in a square, 18 m on each side (Figure 2). Well 22S is constructed with a screen in four separate intervals in the saturated alluvium and can be pumped at a high rate, whereas wells 22PA, 22PB, and 22PC essentially are nested piezometers that also can be used as tracer injection wells and can be pumped at very low rates for sampling.

Between December 2004 and January 2005, two single-hole, injection-pumpback tracer tests were conducted in well 22S. From January to March 2005, a cross-hole tracer test was conducted by pumping the second screened interval from the surface (screen #2, at a depth from 201.5 to 231.8 m)[1] in 22S and injecting tracers into corresponding intervals in 22PA and 22PC. The water table is at a depth of about 144.5 m at the well complex.[1] From August to October 2005, a second cross-hole tracer test was conducted, also by pumping the screen #2 interval in 22S, but injecting tracers only in the corresponding interval of 22PA (this last test is not presented in this paper).

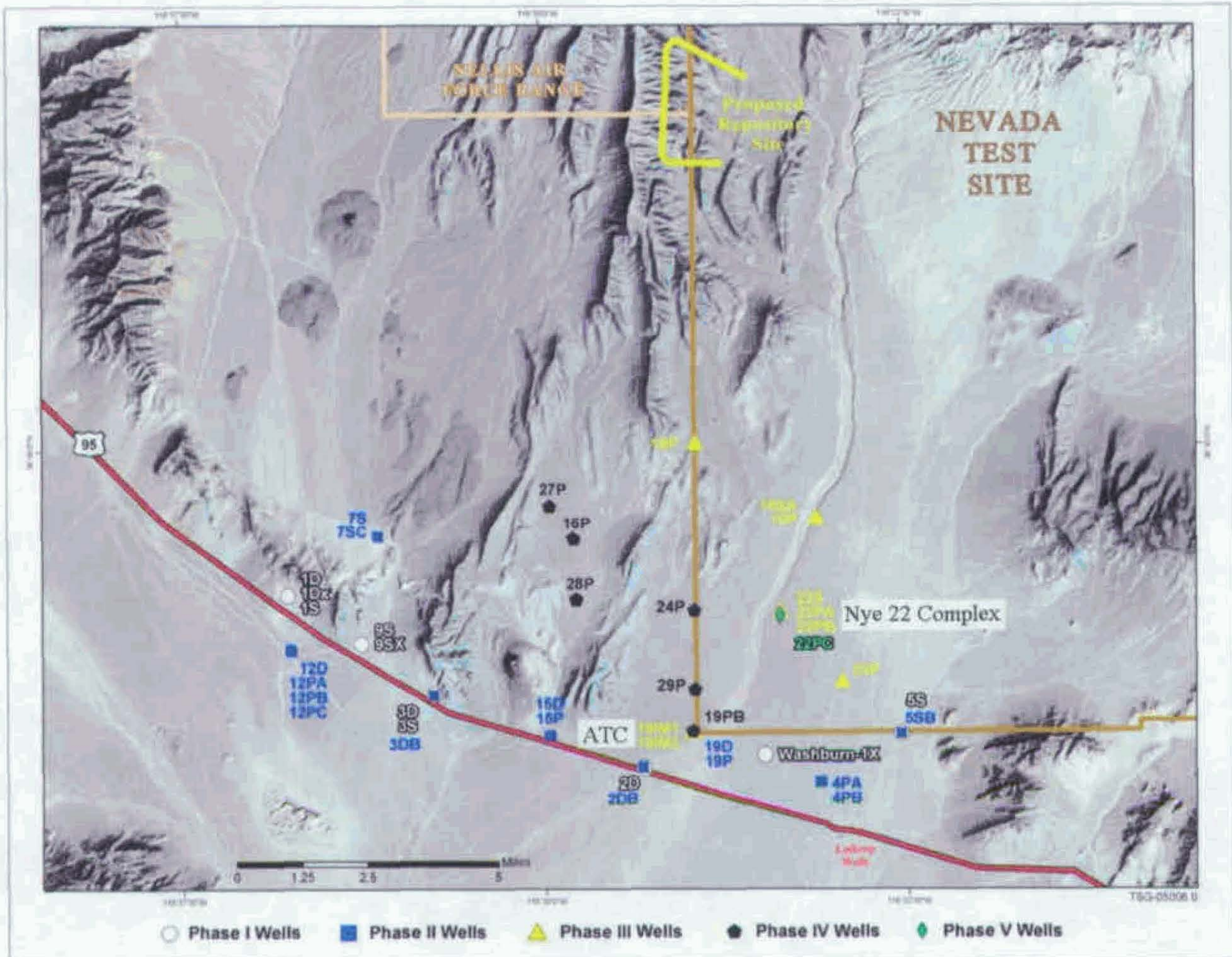

Figure 1. Locations[1] of the Nye County Early Warning Drilling Program (NC-EWDP) wells, specifically the Nye 22 Complex (NC-EWDP-22S, -22PA, -22PB, and -22PC) and the Alluvial Testing Complex, ATC (NC-EWDP-19D, -19P, -19PB, -19IM1, and -19IM2).

In the first injection-pumpback tracer test in well 22S, 1 kg of pentafluorobenzoic acid (PFBA) and 3 kg of sodium iodide (NaI) were injected into screen #2 on December 2, 2004. Tracer injection was followed by the injection of approximately 79,485 liters (L) of non-tracer-laden chase water previously pumped from well 22S. The injected tracer plume was allowed to drift under natural gradient conditions for 3 days. After the drift stage, the plume was pumped back out of the well at the rate of 2.97 L/second (s) for approximately 4 days, ending on December 10, 2004. The PFBA breakthrough curve is presented in Figure 3 (the NaI breakthrough curve, which is almost identical, is not shown). Apparent overestimation of simulated mass under the curve is compensated for by underestimation in the long tail, which is only partially shown.

To analyze the test, a homogeneous Modflow-with-transport[2] model was constructed. The model had one 30.5-m-thick layer discretized into a 0.3-m by 0.3-m areal grid. The only boundary conditions imposed on the model were upgradient and downgradient specified heads calculated so as to represent the natural hydraulic gradient over the modeled area. The following best-fit parameter values were calculated, except when a source is noted, by varying them to obtain a fit between calculated and observed breakthrough curve concentrations: horizontal hydraulic conductivity[3] (Kx and Ky) of 1.4×10^{-4} m/s; natural hydraulic gradient of 0.00045 m/m; (specific discharge, or Darcian flux, of 2 m/yr, calculated from Kx, Ky, and the natural hydraulic

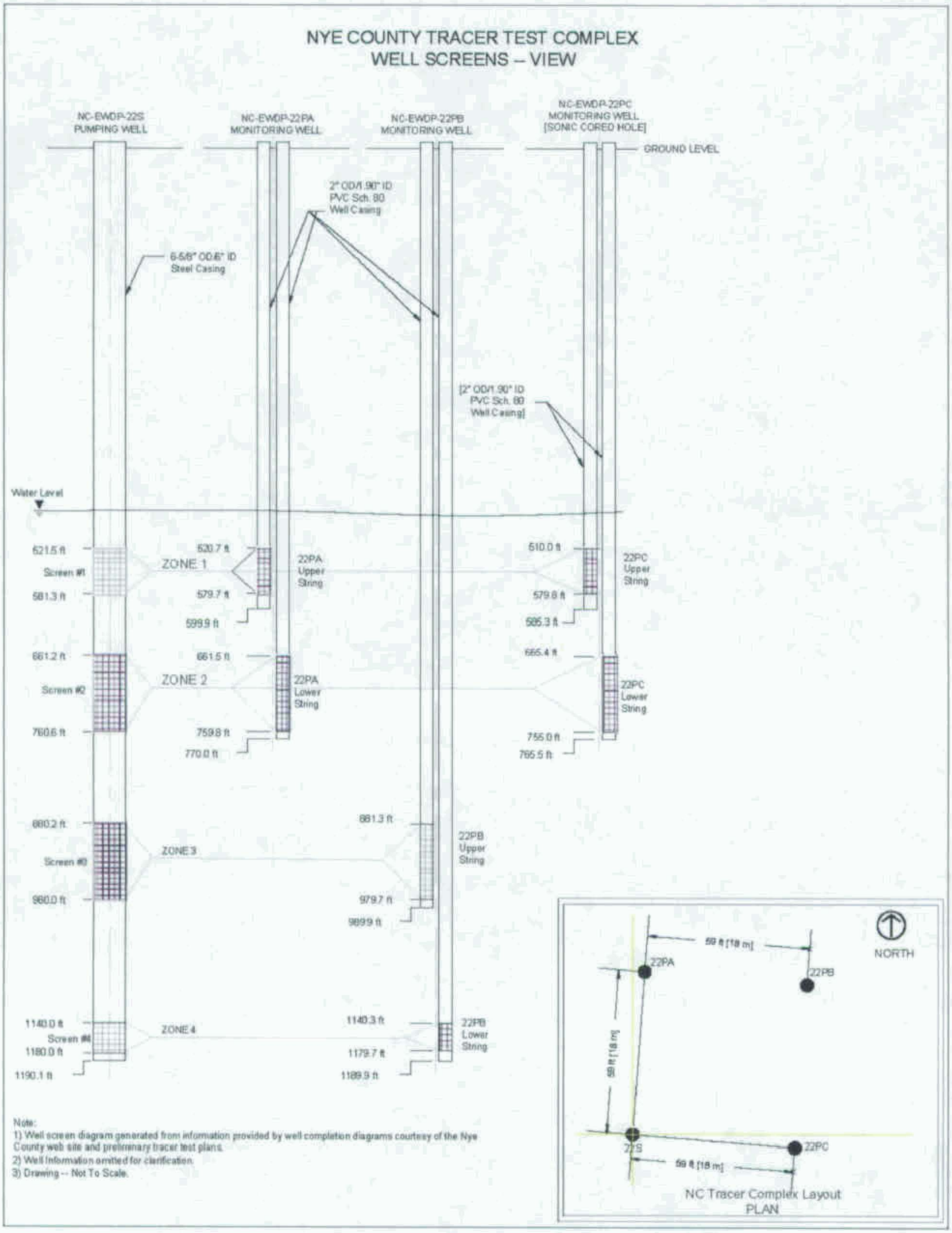

Figure 2. Well layout and screened intervals for the Nye County Early Warning Drilling Program (NC-EWDP)-22 testing complex, southern Yucca Mountain, Nevada

gradient); effective flow porosity of 1.0 x 10^{-1}; longitudinal dispersivity of 0.30 m, and transverse horizontal dispersivity of 0.03 m. Four Modflow PERIODs were established for tracer injection, tracer chase, drift, and pumpback. The simulated breakthrough curve is shown with the actual PFBA data in Figure 3.

In the second injection-pumpback tracer test in well 22S, 1 kg of 2,3,4,5 tetrafluorobenzoic acid (TeFBA) and 3 kg of NaI were injected into Screen #2 on December 13, 2004. Tracer injection was followed by the injection of approximately 79,485 L of non-tracer-laden chase water previously pumped from well 22S. The injected tracer plume was allowed to drift under natural gradient conditions for approximately 4 weeks. After the drift stage, the plume was pumped back out of the well at the rate of 2.97 L/s starting on January 13, 2005. The TeFBA breakthrough curve is presented in Figure 4 (the NaI breakthrough curve, which is almost identical, is not shown).

The Modflow-with-transport model created for analyzing the 3-day-drift, injection-pumpback tracer test also was used to analyze the 4-week-drift test. Using the same hydraulic and transport parameters used to obtain a fit between calculated and observed breakthrough curve concentrations for the first test, but with the four Modflow PERIODs defined to represent the conditions of the second test, the simulated TeFBA breakthrough curve is shown in Figure 4 with the actual data.

The two injection-pumpback tracer tests, therefore, have been analyzed consistently by postulating hydraulic and transport parameters for the area surrounding well 22S as represented by a Modflow-with-transport model and then defining the four PERIODs to conform to the actual conditions of the two tests, which were different. The fits (obtained by using the Kx and Ky values from Nuclear Waste Repository Project Office[3] and varying the natural hydraulic gradient, flow porosity, longitudinal dispersivity, and transverse horizontal dispersivity) are not as close as can be obtained by fitting the breakthrough curve of each test with its own optimal transport parameter set (natural gradient, porosity, and dispersivity), but represent an important effort to obtain the underlying aquifer tracer-test-invariant transport parameters for the 22S near-well environment.

In the first cross-hole tracer test, 8.5 kg of 2,4,5 trifluorobenzoic acid (TFBA), 25 kg of lithium bromide (LiBr), and 97 kg of lithium chloride (LiCl) were injected on January 14, 2005 into the screen-#2-equivalent piezometer (zone 2) of well 22PA while screen #2 of well 22S was being pumped at 2.97 L/s. (The 2.97 L/s pumping from 22S also served as the pumpback for the second, 4-week-drift, injection-pumpback tracer test in 22S just described). Nearly simultaneously with the TFBA and LiBr injection into 22PA, 15 kg of 2,6 difluorobenzoic acid (DFBA) was injected into the screen #2-equivalent piezometer (zone 2) of 22PC (the TFBA and DFBA breakthrough curves in 22S are shown in Figure 5; data for Li, which is sorptive, are not presented or analyzed in this paper). The objective was to have two plumes, one from 22PA and the other from 22PC, migrate to the pumped well 22S in orthogonal directions to determine any large-scale anisotropy in transport parameters caused by heterogeneity in the aquifer. Also, results from the cross-hole tests, with 18 m interborehole distances, were expected to characterize a larger volume of the aquifer than the near-well information obtained from the single-hole tests. Furthermore, it was hoped that results from interpreting the cross-hole tests would aid in developing methodology to extrapolate effective flow porosity and longitudinal dispersivity estimates from analyzing the single-well tests.

From the 2,4,5 TFBA breakthrough curve (blue curve, top part of Figure 6), the derivative curve was calculated (red curve, bottom part of Figure 6); it shows three inflection points indicating three separate arrivals, or flow paths. The breakthrough curve was separated into three breakthrough curves (Figure 7) representing each of the three arrivals, or flow paths, by matching the peaks of the individual breakthrough curves with the inflection points identified from the derivative curve. The separation is not unique and reflects the judgment of the analyst. The three breakthrough curves of these three separate arrivals were analyzed by the Moench analytical solution to the advection-dispersion equation[4,5] to calculate a range of 1.2 to 11 x 10^{-2} for effective flow porosity and 0.30 to 3.0 m for longitudinal dispersivity for the three flow paths. The masses of tracer assumed to be associated with the three flow paths in Figure 7 were apportioned to the areas under the corresponding breakthrough curves (curves 1, 2, and 3), resulting in 7 , 26, and 67 percent of the total injected mass for flow paths 1, 2, and 3, respectively. The same pumping rate of 2.97 L/s was assumed when analyzing each of the three arrivals/flow paths. However, in order to match a different theoretical Moench breakthrough curve to the actual breakthrough curves of each of the three flow paths in Figure 7, different effective aquifer thicknesses through which the tracer moved had to be assumed for each arrival/flow path. An effective aquifer thickness of 42.7 m was assumed for flow path 1; 39.6 m for flow path 2; and 34.7 m for flow path 3. The individual Moench analyses for the three flow paths yielded effective flow porosity values of 1.2 x 10^{-2}, 4.0 x 10^{-2}, and 11 x 10^{-2}; and longitudinal dispersivity values of 0.30 m, 3.0 m, and 2.4 m, for

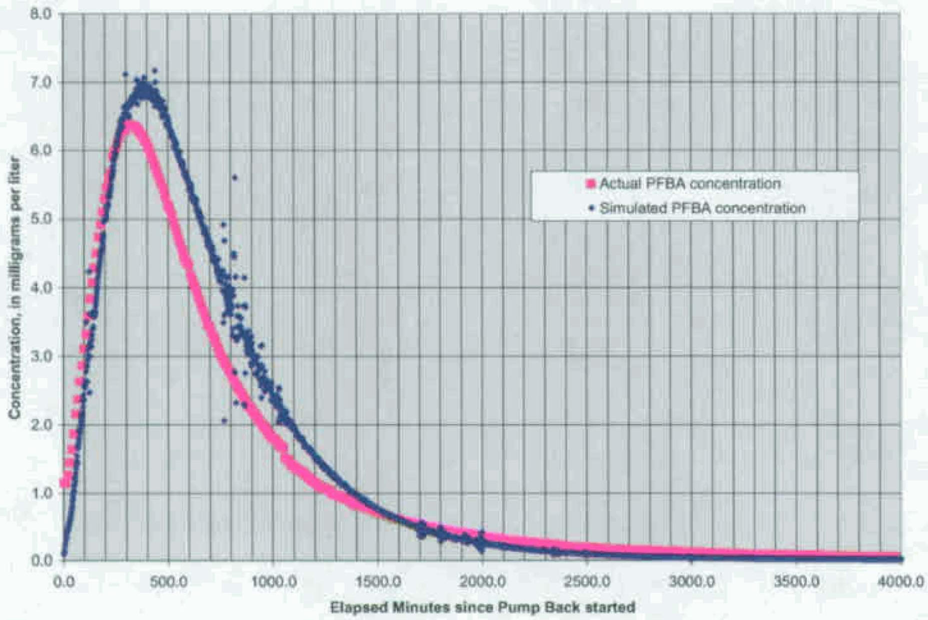

Figure 3. Breakthrough curves for Three-day drift, Injection-pumpback tracer test in well NC-EWDP-22S, southern Yucca Mountain, Nevada, from December 2 to 10, 2004, with three-day drift, simulated with Modflow-with-transport code[2] (Particle-tracking nature of Modflow-with-transport code gives the simulated breakthrough curve a scatter that resembles, but should not be confused with, an actual breakthrough curve. Apparent overestimation of simulated mass under the curve is compensated for by underestimation in the long tail, which is only partially shown).

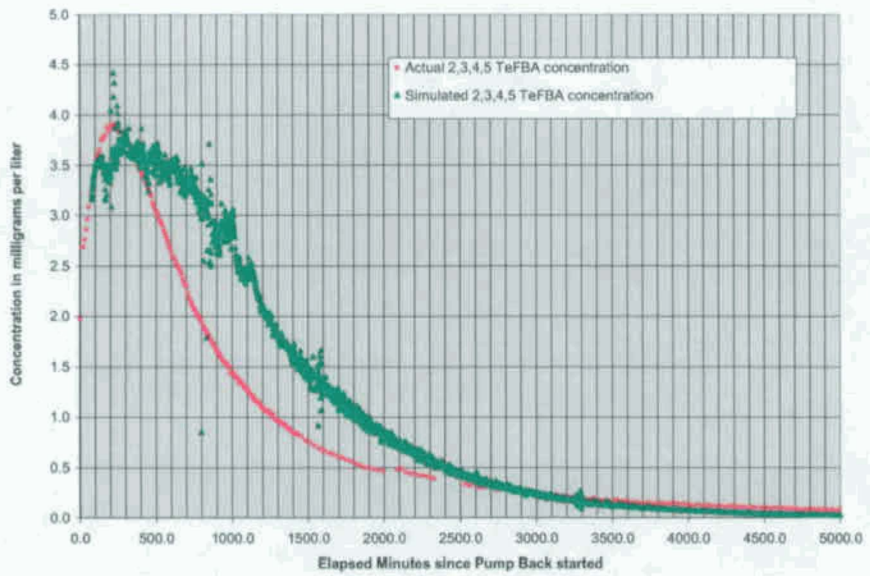

Figure 4. Breakthrough curves for Four-week-drift Injection-pumpback tracer test in well NC-EWDP-22S, southern Yucca Mountain, Nevada, from December 13, 2004, to January 17, 2005, simulated by Modflow-with-transport code[2] (Particle-tracking nature of Modflow-with-transport code gives the simulated breakthrough curve a scatter that resembles, but should not be confused with, an actual breakthrough curve. Apparent overestimation by the model of mass under the curve is compensated for by underestimation in the long tail, which is only partially shown).

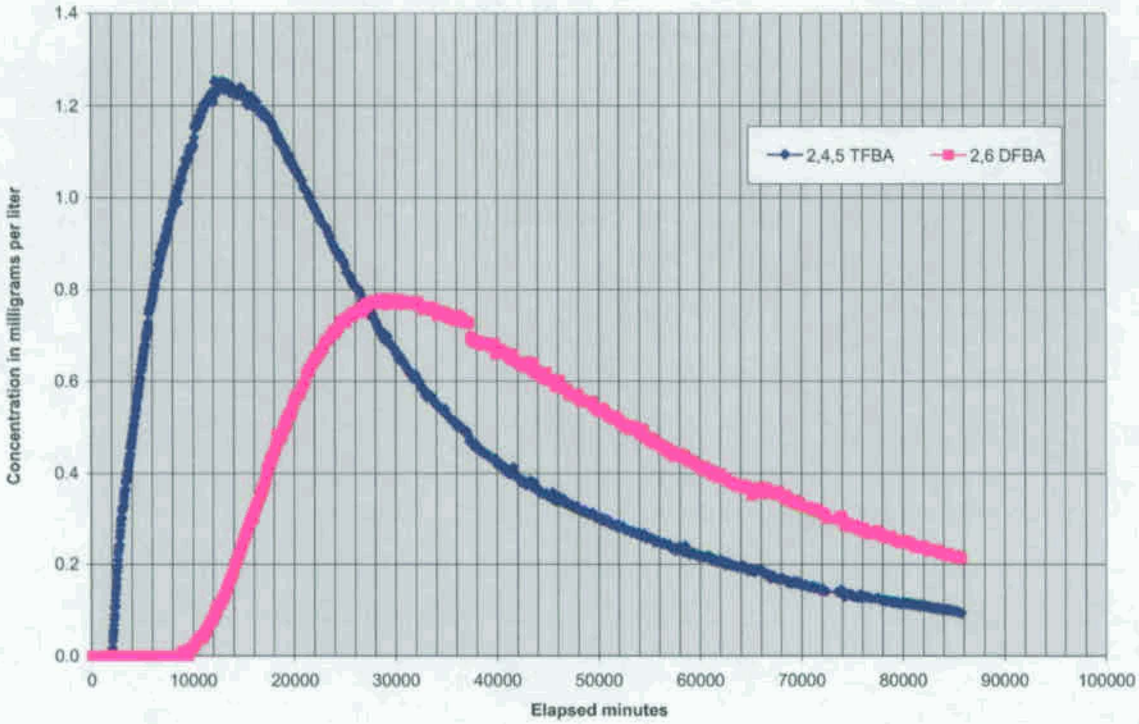

Figure 5. Breakthrough curves at well NC-EWDP-22S for tracer test in which 2,4,5 TFBA is injected into the screen-#2-equivalent piezometer (zone 2) of well NC-EWDP-22PA and 2,6 DFBA is injected into the screen-#2-equivalent piezometer of well NC-EWDP-22PC, southern Yucca Mountain, Nevada.

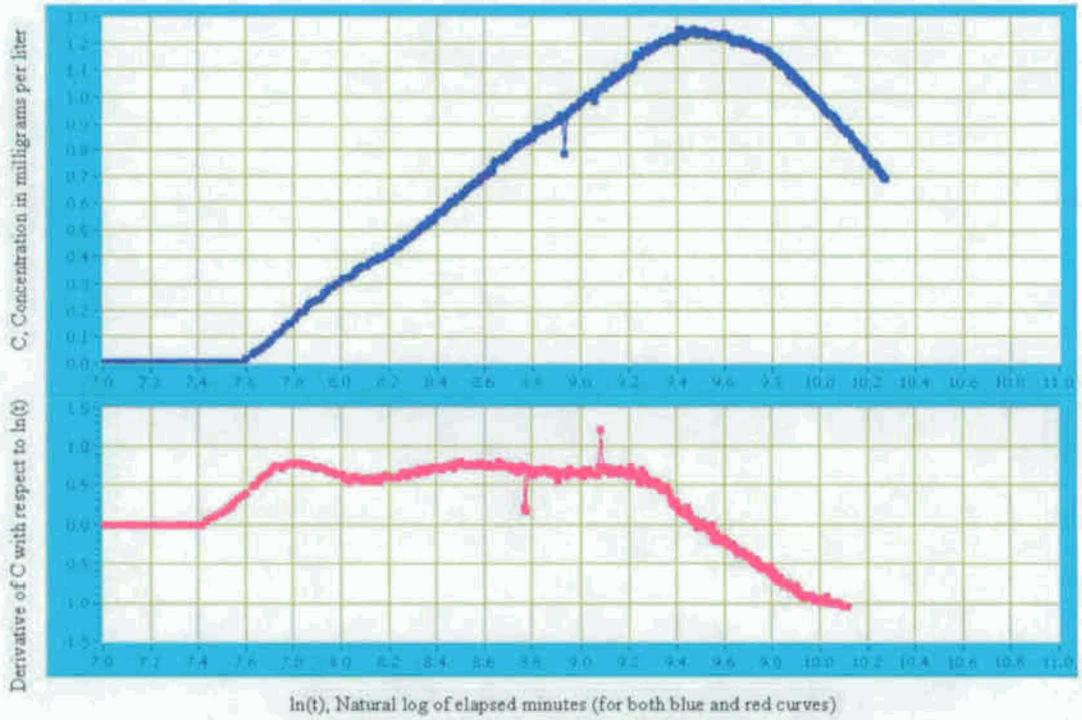

Figure 6. Breakthrough curve in well NC-EWDP-22S for tracer test in which 2,4,5 TFBA is injected in well NC-EWDP-22PA (blue curve), and its derivative (red curve).

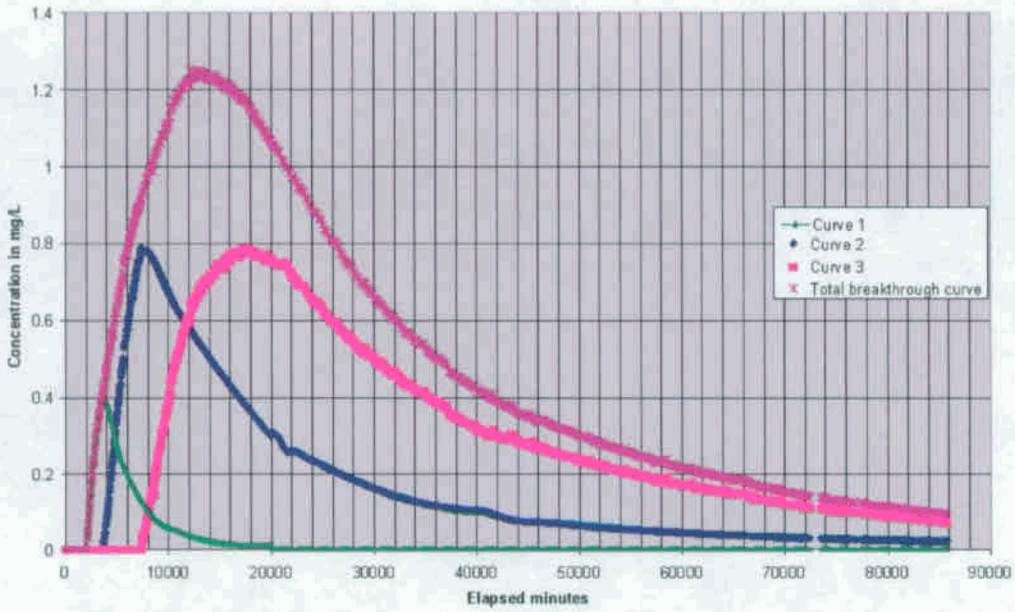

Figure 7. Component breakthrough curves constituting the total breakthrough curve at well NC-EWDP-22S for tracer test in which 2,4,5 TFBA is injected into the screen-#2-equivalent piezometer (zone 2) of well NC-EWDP-22PA, southern Yucca Mountain, Nevada, where the multiple arrivals/flow paths are inferred from the derivative curve of Figure 6. Mass fraction for curve 1 was 7 percent, curve 2 was 26 percent, and curve 3 was 67 percent.

flow paths 1, 2, and 3, respectively. These values contrast with the value of 1.0×10^{-1} for effective flow porosity and 0.30 m for longitudinal dispersivity for the Modflow-with-transport model simulations used to fit the breakthrough curves of the two single-well injection-pumpback tracer tests, previously discussed. A dual-porosity (rather than single-porosity) Moench theoretical breakthrough curve was needed to fit to the breakthrough curves for flow paths 2 and 3, showing that the cross-hole test indicates some solute diffusion into the stagnant portion of the alluvial aquifer, as opposed to only advection in the flow path(s) of the alluvium. The storage porosity associated with this diffusion into stagnant water is on the order of 5 to 7 percent.

The derivative of the breakthrough curve in well 22S of the 2,6 DFBA injected into 22PC did not exhibit any inflection points, so the breakthrough curve was analyzed as a single arrival by the Moench analytical solution. Assuming a pumping rate of 2.97 L/s and an aquifer thickness of 42.7 m, the analysis produced an effective flow porosity of 2.0×10^{-1} and a longitudinal dispersivity of 3.0 m.

The Moench-solution estimates of longitudinal dispersivity of 0.30 to 3.0 m in the 22PA-to-22S direction (north-south) and 3.0 m in the 22PC-to-22S direction (east-west) are fairly consistent.

The fact that the effective flow porosity estimates in these two directions change from a range of porosities of 0.012 to 0.11 (north-south) to a porosity of 0.20 (east-west), however, indicates that heterogeneity plays an important role in these tracer test results in the alluvium. The effective flow porosity from north to south at the NC-EWDP-22 location is about half of that from east to west, and, because transport (interstitial) velocity is inversely proportional to the effective flow porosity, plumes traveling from east to west (approximately perpendicular to the direction of alluvial deposition) may travel at average velocities two times smaller than the velocities of plumes traveling from north to south (approximately parallel to the direction of alluvial deposition). Because of these results for the cross-hole tests, the Modflow-with-transport model assuming homogeneity in the aquifer that was used to fit the breakthrough curves of the two single-well tracer tests (presented earlier) needs to be modified in the future to incorporate heterogeneity that is consistent with all of the single- and cross-hole tracer test responses at the Nye County 22 testing complex.

III. CONCLUSIONS

Two single-hole injection-pumpback tracer tests and one cross-hole tracer test conducted at the Nye County 22 Complex were analyzed to obtain transport properties of the alluvium. Preliminary results indicate effective flow porosity values ranging from 1.0×10^{-2} for an individual flow path to 2.0×10^{-1} for composite flow paths, longitudinal dispersivity ranging from 0.3 to 3 m, and a transverse horizontal dispersivity of 0.03 m. (Estimates of longitudinal dispersivity can be influenced by the extent of mixing of the tracer in the injection well.)

The parameter values for effective porosity and longitudinal and transverse dispersivity were obtained by a limited sensitivity analysis. These parameter values satisfy the governing advection-dispersion equation for solute transport along with the conditions of the tests and make the difference between simulated and observed breakthrough concentrations (the objective function) fairly small. To obtain optimal parameter values that not only minimize the objective function but ensure that any solution is not a local, but a global minimum, extensive sensitivity analyses and (or) formal parameter estimation techniques would be needed. Preliminary estimates also indicate directionality in parameter estimates (for example, the effective porosity in the north-south direction is different from that in the east-west direction), most likely the result of heterogeneity-induced large-scale anisotropy (as opposed to point anisotropy: anisotropy at each spatial point in the medium). When finalized, these results will contribute to determining the transport characteristics of the alluvium, an important element of understanding flow and transport in the saturated zone at Yucca Mountain, Nevada.

ACKNOWLEDGMENTS

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